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LCI METHODOLOGY AND DATABASES

Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea

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Abstract
Purpose In Korea, natural gas is widely used as city gas, fuel for electricity generation, and fuel for transportation (e.g., city bus). However, the environmental impact associated with the use of natural gas in Korea has not been paid much attention to. In this study, well-to-wheel (WTW) analysis on the greenhouse gas (GHG) emissions and energy uses associated with natural gas in Korea was performed by considering every step from feedstock recovery to final use in the vehicle operation.
Methods The raw data used in the analysis were mainly provided by Korean natural gas industry and related associations. The additional information, especially for the processes in foreign countries, was also collected by literature survey. We adopted the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model as a base WTW analysis tool, which was developed by the U.S. Argonne National Laboratory. However, the WTW analysis on natural gas in Korea is far different from that of the U.S, because ~99 % of natural gas used in Korea is imported from the oversea countries in the form of liquefied natural gas (LNG). For this reason, detailed parameters in GREET were changed for Korean situation, and especially, significant modifications were made on liquefaction, LNG transportation and storage, and re-gasification processes.
Results and discussion As a result of the analysis, the well-to-pump GHG emissions of city gas and compressed natural gas are calculated as 25,717–30,178 and 28,903–33,422 g CO_2 eq./GJ_{Fianl_fuel}, respectively. The WTW GHG emission of compressed-natural-gas-fueled city bus is calculated as 1,348–1,417 g CO_2 eq./km. These values are relatively larger than those of the U.S., because most of the natural gas used in the U.S. is transported by pipeline in a gaseous state, which typically takes less energy and associated GHG emissions, as compared to the import of LNG in Korea. Finally, sensitivity analysis is performed on the parameters, which have either range of values among various sources or uncertainties due to lack of accurate information.
Conclusions The results show that further investigation on three parameters, i.e., CO_2 venting during natural gas processing, CH_4 leakage in Korea, and CH_4 leakage during recovery process, would be helpful to further improve overall accuracy of the analysis.

Keywords Automotive fuels · Fuel cycle analysis · Greenhouse gas emission · Natural gas · Well-to-wheel analysis

1 Introduction

As mankind has mainly used fossil fuels to meet their increasing energy needs, environmental change such as global warming became one of the most important issues that should be resolved to build the sustainable future. To evaluate the impact from the use of an energy resource on the environment, life-cycle-based approaches such as life cycle assessment, fuel cycle analysis, ecological footprint, and life cycle risk management, were introduced as promising methodologies (Curran 2013). Although the focus might be different among these methods, the environmental impacts during not only the end use but also all the life cycle processes are evaluated. Therefore, they can provide the measures to understand the lifetime environmental impact from the use of the resource.

Among these methods, fuel cycle analysis is commonly referred to as well-to-wheel (WTW) analysis, which is

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focused on transportation fuels. In WTW analysis, the fuel life cycle can be categorized into well-to-pump (WTP), i.e., from fuel well to pump in the gas station, and pump-to-wheel (PTW), i.e., from pump to the end use in the vehicle.

Since the transportation sector takes large responsibility for greenhouse gas (GHG) emissions, regulations based on the WTW analysis were enforced by several governments in developed countries. For instance, Low Carbon Fuel Standard (LCFS), which regulates the GHG emissions of transportation fuels during the WTP processes, was approved by the government of California and enacted in January 2011. In addition, Renewable Fuel Standard (RFS), which uses the WTP GHG emissions to set the standards for renewable fuels, was approved by the federal government of the U.S. and enacted in September 2007. Especially, the RFS is now being considered by the Korean Government and the Korean National Assembly, and the legislation is expected soon. Therefore, it is important to build the WTP GHG database on the automotive fuels in Korea.

In the present paper, we perform the WTW analysis on natural gas in South Korea, focusing on the associated GHG emissions and energy uses. It is noted that natural gas is one of the major transportation fuels in Korea, mainly for city bus. Previous WTW analysis on natural gas has been performed mainly in developed countries, such as the United States, Europe, and Japan (ANL 2012; Edwards et al. 2011a, b; TMC 2004). Although there was a WTW study on Korean natural gas (Wie et al. 2001), most of the analysis was based on Japanese data and lack details. Additionally, National Life Cycle Inventory database (KLCI 2013) of fossil fuels, including natural gas, was established by Korea Environmental Industry and Technology Institute, but the data used for the analysis of natural gas is somewhat outdated and has the limitation that the validity of analysis is not readily verified since the details are not open to public.

Korea does not reserve natural gas enough to meet the domestic demands, and cannot import natural gas by pipeline due to geopolitical location. Therefore, ~99 % of natural gas consumed in Korea is imported in the form of liquefied natural gas (LNG) by LNG carrier and re-gasified in Korea. This fact makes the WTW analysis of natural gas in Korea different from that of the U.S. Therefore, in this study, significant emphasis was made on the analysis of the processes regarding LNG, i.e., liquefaction, transportation and storage of LNG, and re-gasification.

The main body of this paper consists of three parts. In Section 2, the brief outline of the fuel cycle processes regarding Korean natural gas is discussed. In Section 3, the key parameters and assumptions applied for the analysis are introduced by each individual process. In Section 4, the WTW results and the comparison with other representative countries are presented, along with the results from the sensitivity analysis.

2 Well-to-wheel analysis approach

The fuel cycle of natural gas in Korea can be modeled as seven processes in Fig. 1. For the first step, raw natural gas is recovered in the extraction field. Then it is processed into the product-level natural gas in the processing plant. For countries that produce domestic natural gas or import by pipeline, the whole fuel cycle of natural gas consists of these two processes and transportation process by pipeline.

However, for Korean application, after being processed, natural gas is transported to liquefaction plant in producing countries, where it is liquefied to LNG, and then transported to Korea by LNG carrier. In Korea, LNG is stored in LNG storage, re-gasified in the re-gasification facility, and distributed by pipeline. The five processes above correspond to the fuel cycle of natural gas used in power generation sector as well as city gas in Korea which is usually for residential cooking or heating.

For automotive application, the natural gas is compressed to the required pressure, and therefore gas compression process should be considered. The final step of the fuel cycle is vehicle operation, where compressed natural gas (CNG) is combusted to produce power for CNG vehicle.

The present analysis was performed based on the software "GREET 1[1] (version 2012)", which was developed in the U.S. Argonne National Laboratory (ANL). This program is used to perform the WTW analysis of automotive fuels by the U.S government. We changed all the detailed data in GREET for Korean application, and modified GREET framework as well to consider the processes which are not originally included, such as re-gasification of LNG. The Korean data were mainly provided by Korea Gas Corporation (KOGAS) and Korea Association for Natural Gas Vehicles (KANGV). The additional information was collected by literature surveys as well as based on our own analysis. It is noted that KOGAS is the only company that imports, stores, re-gasifies, and distributes natural gas in South Korea. Therefore, the KOGAS data covers the whole natural gas in Korea.

In the following paragraphs, some of the important terms and the basic calculation framework are explained. First of all, we use the term "process fuel" to indicate the fuel that is consumed to provide energy to the devices or facilities for performing the designated process. For example, during natural gas recovery, both diesel and electricity are mainly used as process fuels to operate facilities that extract natural gas from the well. We also define "efficiency" of a certain process as the energy of product divided by the sum of the energies of product and process fuels used in the process, as in Eq. 1. Therefore, if the efficiency of a certain process

[1] Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation.

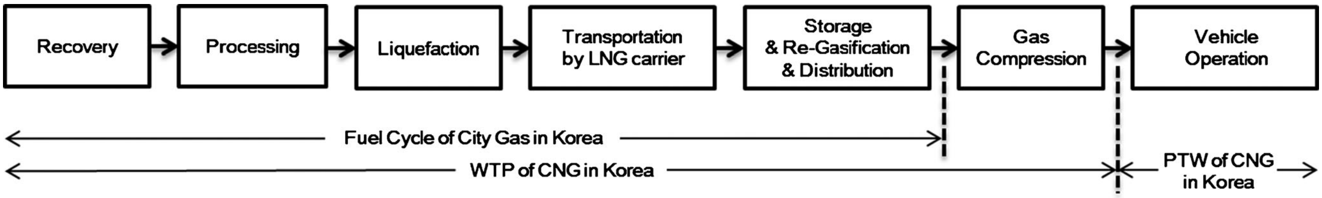


Fig. 1 Fuel cycle of natural gas in South Korea

is known, the total "energy use" of process fuels to produce the unit energy of the product can be easily calculated.

$$\text{Efficiency} = \frac{\text{Energy of product}}{\text{Energy of product of process fuels}}$$

$$\text{or } \frac{\text{Energy of process fuels}}{\text{Energy of product}} = \frac{1}{\text{Efficiency}}\text{-1} \quad (1)$$

"Process fuel share" means the energy share of each process fuel used in the process. For example, if the total energy of process fuels used to produce the unit energy of product is 5,000 kJ/GJ, and the process fuel share is 40 % for diesel and 60 % for natural gas, then the amounts of diesel and natural gas used are 2,000 and 3,000 kJ/GJ, respectively. For calculating GHG emissions, the values of "combustion technology share" for each individual process fuel and "emission factor" of each combustion technology should be known as well. From the above example, if the combustion technology share of diesel fuel in the designated process is 30 % for stationary engine and 70 % for turbine, the energy used in the stationary engine and the turbine would be 600 and 1,400 kJ/GJ, respectively. Then, we can finally calculate the GHG emissions from these combustion technologies by multiplying the emission factors associated with each combustion technology and the energy uses. Emission factors are typically defined as the quantities of the relevant species emissions from the combustion of unit energy of fuel. For example, the CO_2 emission factor of diesel stationary engine and turbine are 73,366 and 74,103 g CO_2/GJ, respectively (ANL 2012). Finally, the total emissions from the process are calculated by summing all the products of emission factors and energy uses for the combustion technologies of all the process fuels considered.

For the aforementioned parameters, we use the data from KOGAS for the processes that are occurred in Korea, while the various references are used for the processes out of country. Especially, the combustion technology share is mostly referred to ANL reference (ANL 2012). For emission factors, we considered two major references, Intergovernmental Panel on Climate Change (IPCC 2006) and ANL (ANL 2012). However, both references are mainly based on the data of the U.S. Environmental Protection Agency (EPA), and thus the values from them are quite similar to each other. For comparison, we choose two major combustion technologies, i.e., NG boiler and NG turbine, which take the largest shares in the fuel cycle of natural gas in Korea, and compare the emission factors, as shown in the Table 1. It is noted that the values are very similar to each other, only except the N_2O emission factor for NG turbine. Finally, since the data in the ANL reference are much richer and detailed than those in the IPCC report, we decided to use the emission factors of the former.

3 Key parameters and assumptions

The key parameters, assumptions, and data sources used in the analysis are discussed in this section. Each subsection is devoted to individual process in Fig. 1. Before going through each subsection, the parameters and assumptions generally applied for overall analysis are introduced in the following paragraphs.

Firstly, this study covers CO_2, CH_4 and N_2O for the GHG emission. We use the global warming potentials (GWPs) of CO_2, CH_4 and N_2O as 1, 25 and 298, respectively (IPCC 2006). The CO_2-equivalent GHG emission is calculated by summing the products of each gas emission and its GWP.

Secondly, the amount of GHG emissions in this paper is presented in the form of "g CO_2 eq./GJ_{Final_fuel}" or "g CO_2 eq./$GJ_{Process}$". The former (g CO_2 eq./GJ_{Final_fuel}) refers to a certain amount of CO_2-equivalent GHGs emitted to produce 1 GJ of final fuel at the end of fuel cycle. The latter (g CO_2 eq./$GJ_{Process}$) implies a certain amount of CO_2-equivalent GHGs emitted to produce 1 GJ of product at a certain process. For example, 1 g CO_2 eq./$GJ_{Process}$ at natural gas recovery (step 1 in Fig. 1) means 1 g of CO_2-equivalent

Table 1 Comparison of two major emission factors between ANL and IPCC references

(g/GJ)		NG boiler	NG turbine
CO_2	ANL	56,263	56,265
	IPCC	56,100	56,100
CH_4	ANL	1.043	4.038
	IPCC	1	4
N_2O	ANL	1.043	1.422
	IPCC	1	1

GHGs emitted to produce 1 GJ of raw natural gas, which is a product of that step. Since some part of the fuel is usually lost in each process through evaporation or leakage, the GHG emission expressed in g CO_2 eq./GJ_{Final_fuel} is usually bigger than the one in g CO_2 eq./$GJ_{Process}$.

Thirdly, we referred to KOGAS for the properties of NG and LNG. The lower heating value and the density of NG are 50.1 MJ/kg and 0.786 kg/Nm^3, and those of LNG are 49.3 MJ/kg and 449 kg/m^3, respectively. It is noted that a lower heating value of the fuel, rather than higher heating value, is used for the present study, because the water usually exists in the gaseous state after the fuel combustion.

Finally, we do not consider shale gas, because Korea does not import it yet. Also, we only analyze imported natural gas, which takes ~99 % of the whole consumption in Korea, excluding the rest (~1 %) which is produced in the East Sea of Korea.

3.1 Recovery

The fuel cycle of natural gas is started by extraction of raw natural gas, designated as recovery process in this study. As mentioned in Section 2, to calculate the amount of GHG emissions from the process, information on the efficiency and process fuel share should be known primarily. Korea imports natural gas mainly from Southeast Asia and Middle East, while the imported portion of the natural gas used in the U.S is mainly from South America and Middle East. Since there is no better information available for the extraction process in Southeast Asia, we assume that the efficiency and process fuel share would be similar as those of the imported portion of natural gas in the U.S, which correspond to the process efficiency of 95.7 % and the process fuel share of 1 % for residual oil, 11 % for diesel, 1 % for gasoline, 86 % for natural gas, and 1 % for electricity (ANL 2012). In Section 4, we examine the sensitivity of the results from possible errors associated with the assumption above.

Another important parameter on evaluating GHG emissions during the recovery process is the emission from flaring of natural gas in the extraction fields. Although the flared quantity can differ among production fields or countries, the associated GHG emission generally takes a large portion in the WTW GHG results of natural gas. For the analysis of flaring, we use two references which provide the flaring data by individual country.

The first reference is International Energy Statistics (IES), published by the U.S. Energy Information Administration (EIA) (EIA 2010). The statistics contains the amount of CO_2 emission from natural gas flaring in each producing country. The second reference is the statistics report published by the U.S. National Oceanic and Atmospheric Administration (NOAA) (NOAA 2010). The researchers of NOAA estimate the amount of flared gas by the brightness and size of flaring in satellite pictures.

These references contain the aggregate of the flaring quantities both from natural gas and crude oil production fields. Therefore, to get the flaring amount only from natural gas production, we have to allocate the whole flaring quantity into natural gas and crude oil. It is known that the flaring is typically exercised during oil production, rather than in natural gas production, because the associated gas from the oil well is usually flared during oil production due to the shortage of the NG treatment facilities near it. Therefore, the allocation share, 12.7 % for natural gas and 87.3 % for crude oil, is adopted in this study (EII 1994). Based on this allocation, the average flaring amount for natural gas imported in Korea can be calculated by weight averaging the flaring amount in each producing country with the import quantity from it. The data of import quantity was from KOGAS. As a result, we get 447 g CO_2/$GJ_{Process}$ from IES and 581 g CO_2/$GJ_{Process}$ from the report of NOAA. Finally, we use the average value, 514 g CO_2/$GJ_{Process}$, for the analysis and include an error range to show the uncertainty.

Additionally, during the recovery process, CO_2 contained in the natural gas is vented and CH_4 can be leaked during the process due to its gaseous nature. It is reported that the amount of CO_2 venting is not significant, but the amount of CH_4 leakage is relatively large. The final values adopted are 39.24 g CO_2/$GJ_{Process}$ for CO_2 venting and 377.95 g CH_4/$GJ_{Process}$ for CH_4 leakage (Burnham et al. 2011). Because the effect of CH_4 leakage during recovery process on total GHG emissions is large, we will examine the sensitivity of the results from possible errors associated with the reference above, in Section 4. To sum up, the total energy use of the recovery process is 57,061–61,513 kJ/GJ_{Final_fuel} and the amount of GHG emissions is 12,402–12,810 g CO_2 eq./GJ_{Final_fuel}.

3.2 Processing

After extraction, raw natural gas is transported to natural gas processing plant for refining it. Similarly as in the recovery process, without better information on Southeast Asia, we assume that the efficiency and process fuel share are similar as in the U.S. case, and perform the sensitivity analysis about the possible errors on the final results in Section 4. The efficiency is 97.2 % and the process fuel share is 1 % for diesel, 96 % for natural gas, and 3 % for electricity (ANL 2012).

Other major parameter in this refining process is the amount of CO_2 venting. Since raw natural gas contains CO_2, it should be removed to produce final natural gas product, which is vented to the air in the end. The amount of CO_2 venting is different among producing countries, depending on the CO_2 content in raw natural gas. We refer to the two following references for the analysis.

The first reference is the report from the IPCC. According to the reference (IPCC 2006), the amount of CO_2 venting is 0.063 Gg $CO_2/(10^6\ m^3)$ for developed countries and 0.063–0.15 Gg $CO_2/(10^6\ m^3)$ for developing countries and countries with economies in transition. The values can be converted to 1,719 and 1,719–4,095 g $CO_2/GJ_{Process}$ by using the lower heating value and density of natural gas.

The second reference is GHGenius ((S&T)[2] Consultants 2012). In GHGenius, the volume percentage of CO_2 contained in natural gas for each producing country is provided. By weight averaging these data with import quantity from each country, the average percentage of CO_2 contained in the natural gas imported in Korea is obtained, which is 1.967 % in our calculation. Meanwhile, the value for the U.S. is 1.75 % and the associated CO_2 emission is 832 g $CO_2/GJ_{Process}$ (Burnham et al. 2011). By taking the ratio of these two percentages and using the U.S. value, we can calculate the amount of CO_2 venting for Korean natural gas as 886 g $CO_2/GJ_{Process}$.

Because IPCC reveals itself that the uncertainty error regarding the CO_2 venting can be ~1,000 %, which is relatively large, we decided to use the GHGenius data, 886 g $CO_2/GJ_{Process}$, as the main reference, and drew an error bar from 886 to 1,719 g $CO_2/GJ_{Process}$, which is the minimum value calculated from IPCC data.

Additionally, CH_4 is also leaked during the natural gas processing and the value of 29.4 g $CH_4/GJ_{Process}$ is adopted from GREET (Burnham et al. 2011).

Finally, the total energy use of this process is 34,426–35,057 kJ/GJ_{Final_fuel} and the amount of GHG emissions is 4,024–4,996 g CO_2 eq./GJ_{Final_fuel}. It is noted that these figures also include the energy use and the GHG emissions regarding the transportation of natural gas to liquefaction plant, both of which take only small portions of the total, or around 3 % and 5 %, respectively.

3.3 Liquefaction

To transport the natural gas overseas to Korea, it is liquefied first in the producing countries. The main parameters that should be considered in this process are the liquefaction efficiency and the amount of CH_4 venting from LNG storage. Since it is difficult to identify the liquefaction efficiency from individual plants, we, instead, evaluated the worldwide average efficiency of liquefaction. The main liquefaction technologies for LNG plants can be categorized into five: propane mixed refrigerant process (C3MR), cascade, single mixed refrigerant process (SMR), dual mixed refrigerant process (DMR), and AP-X.[2] To calculate the average efficiency, the worldwide capacity share and the efficiency of each technology are required.

The historical worldwide capacity shares of each technology are shown in Fig. 2 (Bosma and Nagelvoort 2009). At the same time, we refer to another reference for the total capacities constructed in these periods. The values are 120 million tons per annum for the period of 1964–2000 and 160 million tons per annum for 2001–2012 (IGU 2012). By using these data, it is possible to estimate the present share of each liquefaction technology as shown in Table 2, with the assumption that all the liquefaction plants built are operating up to 2012. The efficiencies of each liquefaction technology are also listed in Table 2 (Vink and Nagelvoort 1998). Finally, the average efficiency of liquefaction can be calculated, which ranges from 92.4 % to 92.6 %. We use the average value, 92.5 %, as a representative efficiency, and use an error bar for uncertainty. From this average efficiency, the energy use for liquefaction is calculated as 92,786–98,711 kJ/GJ_{Final_fuel}. The process fuel consists of mainly natural gas, and the process fuel share is assumed to be 98 % for natural gas and 2 % for electricity (ANL 2012).

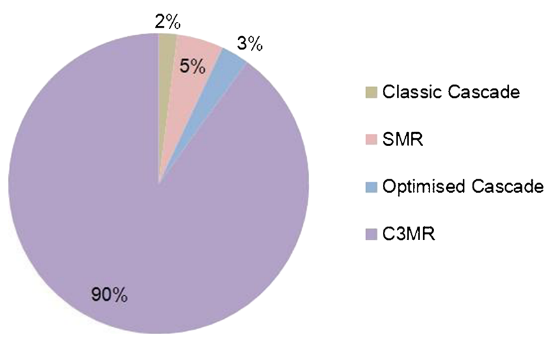
After it is liquefied, LNG is stored for a few days before being shipped out. Because the boiling point of natural gas is −162 °C, LNG tends to boil off inside the storage chamber. Although LNG storages are specially designed for maintaining low temperature, it is impossible to stop boiling off completely. Some portion of this boil-off-gas (BOG) is recovered to LNG, while the rest is vented to the air.

To calculate the amount of CH_4 venting during the storage, the required parameters are duration of storage, boil-off-rate (BOR), and recovery rate. Without better information, we assume 5 days for the average duration of storage at producing countries, and the sensitivity of the results from possible errors associated with the assumption will be investigated in Section 4. To evaluate the BOR, we refer to Gastransport&Techinigaz Inc. (GTT), which is a dominant company in LNG storage market. According to GTT, 0.1 %/day is appropriate for the BOR of LNG storage constructed in land. Finally, 80 % of recovery rate (ANL 2012) is assumed with the uncertainty from 75 % to 90 %. Therefore, the remaining 20 % that is not recovered is vented to the air, and the value is 20.39 g $CH_4/GJ_{Process}$.

3.4 Transportation by LNG carrier

To calculate the energy use and the GHG emission during transportation by LNG carrier, it is necessary to know energy intensity (kJ/ton km), transport distance, cargo payload, and process fuel share for LNG carrier. Energy intensity is calculated from energy consumption (kJ/hp h), horsepower requirement of LNG carrier, load factor, average speed (km/h), and cargo payload of LNG carrier, as in Eq. 2. Here, the load factor

[2] AP-X is a trademark of Air Products and Chemicals Inc. The AP-X technology was developed to improve the maximum capacity over the C3MR technology by adding a nitrogen gas expander cycle.



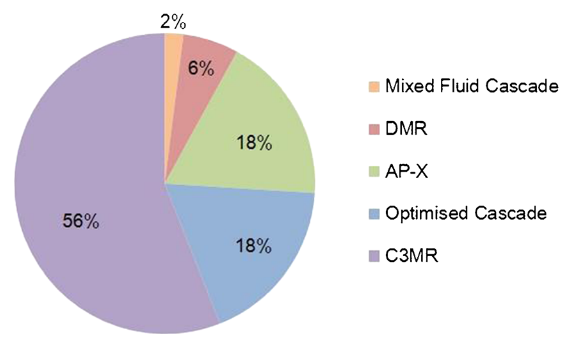


Fig. 2 Liquefaction technology share

is the percentage of installed horsepower that is used for the trip. It is noted that for the purpose of WTW analysis, both ways of travel of LNG carrier should be considered, i.e., from a producing country to Korea and the other way around.

$$\text{Energy intentensity(kJ/ton km)} = \frac{\text{Energy consumption(kJ/hp h)} \times \text{Required horsepower (hp)} \times \text{Load factor}}{\text{Average speed(km/h)} \times \text{Cargo payload(ton)}} \tag{2}$$

For calculating energy consumption (kJ/hp h), we use the method in the ANL reference (ANL 2012). The values are 4,874 kJ/hp h with LNG onboard from a producing country to Korea and 4,949 kJ/hp h without LNG for the other way. KOGAS provided the data for the cargo payload of 60,750 tons, and then the required horsepower for LNG carrier is calculated by Eq. 3 (EPA 2000), and the calculated value is 15,206 hp.

$$\text{Horsepower} = 9,070 + 0.101 \times \text{Cargo payload} \tag{3}$$

For the load factor, we use 80 % when LNG carrier moves from natural gas producing country to Korea, and 70 % when LNG carrier moves back (He and Wang 2000). The difference between these two load factors are mainly due to the weight of LNG, i.e., more horsepower is required when LNG is loaded than otherwise. We used 30.58 km/h for the average speed (EPA 1998).

Table 2 Share and efficiency of liquefaction technologies

1964–2012	Total capacity (million tons)	Technology share (%)	Efficiency (%)
C3MR	196.4	67.72	92.9
Cascade	43	14.83	91.2
SMR	5	1.72	91.6
DMR	11.4	3.93	92.7
AP-X	34.2	11.79	90.4–92.9[a]

[a] The efficiency of AP-X technology was not available in the literature. We arbitrarily assumed the efficiency of AP-X is around the efficiencies of other liquefaction technologies in the literature, i.e., 90.4–92.9 %. Here, the number 90.4 % came from the N_2 expansion technology, which is not included in the analysis, because it has a small share in the market

By using the above data and Eq. 2, energy intensity is calculated as 32.8 kJ/ton km for the trip from the producing country to Korea and 28.8 kJ/ton km for the return.

The transport distance is determined by weight-averaging traffic distance with import quantity from each natural gas producing country to Korean harbor. The import data is provided by KOGAS and the transportation distances are obtained from the web-based, voyage-distance calculating software (Voyage Calculator 2013). From the calculation, 9,300 km is obtained.

During the transportation by LNG carrier, some portion of LNG boils off, similarly as in LNG storage constructed in land. Therefore, LNG carrier is usually equipped with the facility to use BOG as fuel for propulsion. It is typically assumed that the quantity of BOG is enough to provide fuel for LNG carrier, when it moves from a natural gas-producing country to Korea. On the other hand, when the carrier returns to the producing country, we assume that only residual oil is used for propulsion.

Even though a portion of BOG is used for propulsion, there is still some BOG vented to the air. Since LNG carrier does not fully operate the engine all the time, especially when the ship is anchored at the dock, some of the BOG can be vented. To

Table 3 WTP results of natural gas in South Korea

Process	GHG (g CO_2 eq./GJ_{Final_fuel})				Energy Use (kJ/GJ_{Final_fuel})
	CO_2 (g CO_2/GJ_{Final_fuel})	CH_4 (g CH_4/GJ_{Final_fuel})	N_2O (g N_2O/GJ_{Final_fuel})	Total (g CO_2 eq./GJ_{Final_fuel})	
Recovery	2,178–2,436	408–414	0.0436–0.0480	12,402–12,810	57,061–61,513
Processing	2,765–3,717	50–51	0.0384–0.0391	4,024–4,996	34,426–35,057
Liquefaction	5,197–5,562	48–66	0.1244–0.1312	6,423–7,247	92,786–98,711
Transportation by LNG carrier	1,013–1,072	23–60	0.0265–0.0275	1,592–2,592	15,916–18,586
Storage and re-gasification and distribution	454–466	33–83	0.0015–0.0016	1,276–2,532	14,123–16,834
City Gas Total	11,608–13,254	562–674	0.2344–0.2474	25,717–30,178	214,313–230,701
Gas compression	2,936–2,963	10–11	0.0276–0.0279	3,185–3,244	47,133–47,472
CNG Total	14,544–16,217	571–685	0.2625–0.2758	28,903–33,422	261,446–278,173

calculate the amount of CH_4 venting, the similar method as for storage in Section 3.3 is applied. Firstly, the duration of storage can be calculated as the transportation distance divided by the average speed, which is 13 days for the Korean situation. Secondly, BOR at LNG carrier is bigger than that at LNG storage constructed in land because of LNG tank sloshing (Pasquier and Berthon 2012). According to Daewoo Shipbuilding & Marine Engineering Co. (DSME), the typical upper limit at design is 0.15 %/day, but there has also been increasing demand for 0.1 %/day. Based on these data, we use 0.13 %/day as an average. Lastly, we decided to use 90 % of recovery rate with an uncertain range of 85–95 %, which is somewhat higher than that found at land storage, considering the use of BOG for propulsion in LNG carrier, as mentioned above.

3.5 Storage and re-gasification and distribution

After imported, LNG is stored, re-gasified, and distributed in Korea. These three processes are in charge of KOGAS, which provided the data about the total energy use and the GHG emission during these processes. They are 12,129 TJ and 622,750 ton-CO_2-eq. in 2011, which are the official values prepared by KOGAS to be submitted to the Korean government. We converted these data to the amount of energy use and GHG emissions per unit energy of natural gas, by considering lower heating value and total sales volume of NG in Korea, 33,570,000 tons. The calculated value is 15,157 $kJ/GJ_{Process}$ and 376.28 g CO_2 eq./$GJ_{Process}$. According to KOGAS, the process fuel share is 49 % for natural gas and 51 % for electricity.

During these processes there are always CH_4 fugitive emissions, and we refer to the IPCC report and the KOGAS data. The former contains two estimates of CH_4 fugitive emissions during transmission, storage, and distribution for developed and developing countries (IPCC 2006). We use the average of these values, because Korea has both old and new infrastructures for natural gas during the relatively short period of development. The latter also includes the information on CH_4 fugitive emissions. Finally, we average the values from these two sources, which results in 43.01 g $CH_4/GJ_{Process}$ with an uncertainty range from 29.11 to 78.18 g $CH_4/GJ_{Process}$ to reflect on the error range from the IPCC report.

3.6 Gas compression

To use natural gas as a vehicle fuel, it should be compressed to a required pressure at CNG refueling station. According to the Seoul City Gas (SCG), the typical inlet and outlet pressures of the compressor are 0.83 and 24.5 MPa, respectively. To calculate the required work to perform this compression, isentropic efficiency of 65 % for the compressor is considered. From the calculation, we get 47,133–47,472 kJ/GJ_{Final_fuel} as the required work. The compressor is powered only by electricity in Korea.

3.7 Vehicle operation

For PTW analysis, a CNG-fueled city bus is used, because it is the only vehicle class that is officially built for CNG fuel from car manufacturers in Korea. Although some passenger car drivers modify their gasoline-fueled vehicle into CNG-fueled one, it is not the official offering that the manufacturers provide.

The report of the Korea Environment Institute is referred to for the fuel economy and GHG emissions of CNG bus in Korea (KEI 2012).[3] The fuel economy is 2.42 km/Nm^3, which results in the energy use of 16,282 kJ/km during the

[3] The dry weight of the city bus in the report is 11 tons, and the maximum power is 220 kW at 2,000 rpm with an engine displacement volume of 11 l.

PTW process. The emissions values are 7.40 g CH_4/km and 721 g CO_2/km. The N_2O emission is not included in the report, and thus the value in GREET, 0.007 g N_2O/km, is adopted (ANL 2012).

4 Results

Based on the parameters and assumptions described in Section 3, the fuel cycle GHG emissions and energy uses regarding natural gas in Korea are evaluated in Section 4.1. In addition, in order to elucidate the impact of uncertainty of parameters on the overall results, sensitivity analysis on key parameters is performed and the results are discussed in Section 4.2.

4.1 Fuel-cycle GHG emissions and energy uses

For both city gas and CNG, the resulting values of CO_2, CH_4, N_2O and energy use for each process are listed in Table 3. The total GHG emission, expressed in CO_2 equivalent, is the sum of CO_2, CH_4 and N_2O emissions by considering global warming potentials.

Figure 3 shows the WTP results compared with those of the U.S. and Japan. Except for Korea, the graphs show only the total amount of GHG emission, since the categorizations of fuel-cycle processes are somewhat different among reports and thus it is difficult to compare by process. The error bar is included for the Korean case, which is evaluated by considering the minimum or maximum values of the parameters with multiple references, as discussed in Section 3. The result for the U.S. is based on

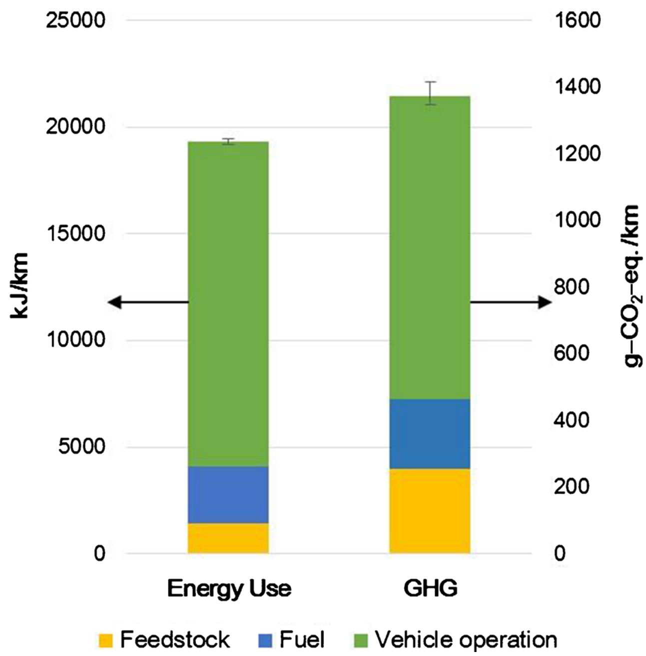


Fig. 4 WTW GHG emission and energy use of CNG city bus

Fig. 3 WTP GHG emission and energy use of CNG

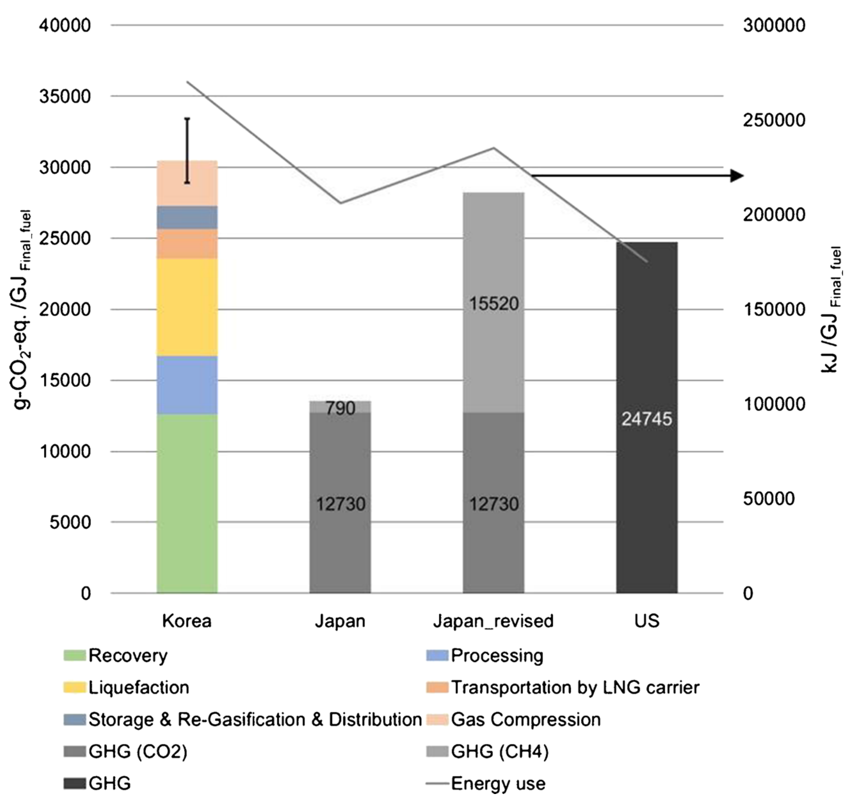


Table 4 Key parameters which have multiple references

Key parameters	Min	Determined	Max
Flaring during recovery (g $CO_2/GJ_{Process}$)	447	514	581
CO_2 venting during processing (g $CO_2/GJ_{Process}$)	935	935	1814
Liquefaction efficiency (%)	92.64	92.51	92.38
LNG recovery rate in foreign country (%)	90	80	75
LNG recovery rate in LNG carrier (%)	95	90	85
CH_4 leakage in Korea (g $CH_4/GJ_{Process}$)	30.71	45.37	82.48

the default values in GREET. The value used for Japan is taken from the report of Toyota (TMC 2004). It is noted that the Toyota report does not include the details for CH_4 emission in their analyses. Therefore, assuming that the overall CH_4 emission for Japan should be similar to that in Korea, we included the revised value of Japan ("Japan_revised" in Fig. 3) by adding all the CH_4 emissions in Korean results to the Japanese CO_2 result. In addition, the amount of energy loss caused by CH_4 emissions is added to the value of total energy use of Japan, which is not considered in the original report.

Since Korea and Japan have a similar geographical location as well as energy situation for natural gas, the resultant values for Korea and Japan (revised) are very close to each other. These values are overall higher than the values for the U.S., which is mainly because Korea and Japan import natural gas as LNG by sea and this involves a large amount of additional energy and associated GHG emissions in liquefaction, transportation by LNG carrier for long distance, and re-gasification processes.

Figure 4 shows the GHG emission and energy use per kilometer of CNG city bus operation. The term "Feedstock" corresponds to feedstock production, i.e., natural gas recovery and processing, while "Fuel" includes the whole processes up to the fueling station, i.e., liquefaction, transportation by LNG carrier, storage and re-gasification and distribution, and gas compression. It is noted that the large portion of the WTW GHG emissions is from the combustion of natural gas in the vehicle ("vehicle operation" in Fig. 4).

4.2 Sensitivity analysis on key parameters regarding WTP GHG emissions

In this section, sensitivity analysis on the key parameters is performed to elucidate the effect of the associated uncertainties on the WTP results. The parameters are classified into two groups: the first group includes the parameters that have multiple references and thus range of values, and the second group includes the major parameters that are assumed to be certain literature values without better information available.

The parameters in the first group are listed in Table 4. Here, the minimum and maximum values of the parameter mean those that lead to the lowest and highest GHG emissions. For example, the larger value for the liquefaction efficiency is shown in the minimum value column, because it results in the lower GHG emissions. It is noted that the ranges in Table 4 correspond to the error ranges discussed in Section 3. To perform the sensitivity analysis on each parameter, the designated parameter is changed in a given range, while all the other parameters are fixed. Then, we analyze the change in the overall WTP GHG emissions.

The result of the sensitivity analysis on the parameters of the first group is shown in Fig. 5. It is demonstrated that most

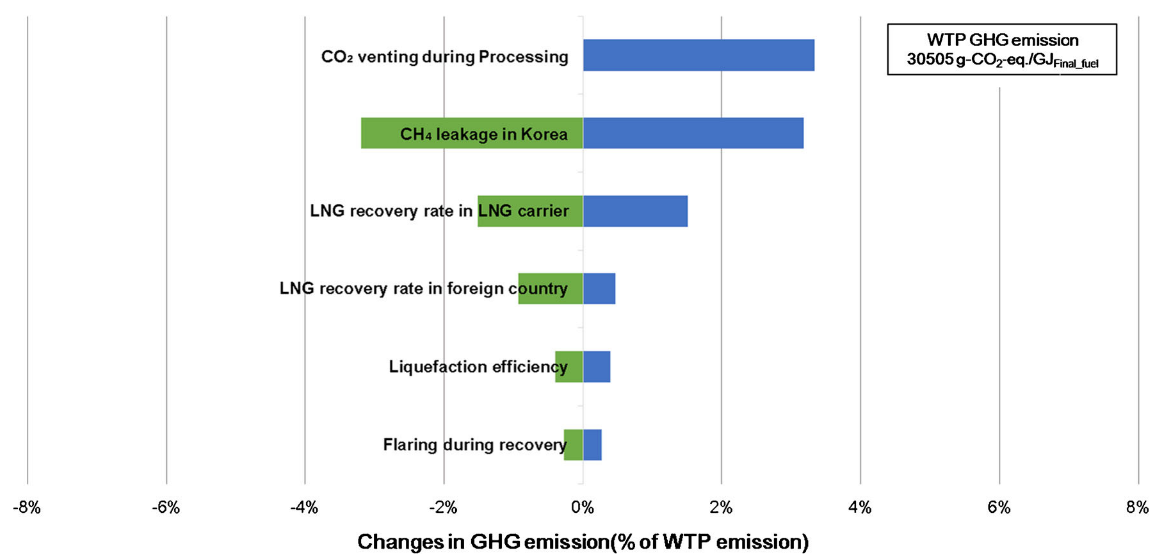


Fig. 5 Results of sensitivity analysis on WTP GHG emission by key parameters described in Table 4

Table 5 Key parameters which are determined by assumptions

Key parameters	Min	Determined	Max
Recovery efficiency (%)	96.11	95.70	95.29
CH_4 leakage during recovery (g CH_4/$GJ_{Process}$)	340.16	377.95	415.75
Processing efficiency (%)	97.47	97.20	96.93
Duration of storage in foreign country (days)	4.5	5	5.5

of the parameters have sensitivities of less than 2 %. However, the amount of CH_4 leakage in Korea and CO_2 venting during natural gas processing in the producing countries show relatively large sensitivities around 3 %.

The parameters in the second group are shown in Table 5. Since it is difficult to determine the expected error ranges for these parameters without further information, in this study, we only examine the sensitivity of each parameter on the final WTP results by changing it within −10 % and 10 % around the assumed value. For recovery and processing efficiencies, the minimum and maximum values are determined by assuming that the process fuel to produce the unit energy of product in each process is consumed 10 % more and 10 % less, respectively.

The result of sensitivity analysis on these parameters is shown in Fig. 6. The most sensitive parameter is CH_4 leakage during the recovery process, which shows around 3.2 % change in the total GHG emissions. On the other hand, the sensitivities of the two efficiencies are relatively small, but they are still non-negligible. Therefore, it would be still desirable to further investigate the assumption that the recovery and processing efficiencies of raw natural gas for Korean application are similar as those in the U.S case. Finally, the sensitivity of duration of LNG storage in foreign country is very low, and thus it is expected that the assumption we made in this study would not lead to significant error in the end.

5 Conclusions

In this study, the WTW analysis on natural gas in Korea was performed. We modeled the whole fuel cycle of natural gas as seven processes and calculated the amount of GHG emission and energy use for each process. As a result of WTP analysis, 25,717–30,178 g CO_2 eq./GJ_{Final_fuel} of GHG emission and 214,313–230,701 kJ/GJ_{Final_fuel} of energy use were evaluated for city gas, and 28,903–33,422 g CO_2 eq./GJ_{Final_fuel} of GHG emission and 261,446–278,173 kJ/GJ_{Final_fuel} of energy use for CNG. By including the vehicle operation of CNG-fueled city bus, the WTW values are calculated as 1,348–1,417 g CO_2 eq./km for GHG emission and 19,202–19,457 kJ/km for energy use. These values are similar to the revised values of Japan but larger than those of the U.S., where there are no energy-consuming liquefaction and re-gasification processes required in fuel cycle processes.

The sensitivity analysis on key parameters was performed to elucidate the effect of data uncertainties on the WTP results. Most of the parameters showed relatively small error sensitivities, but there are several parameters with relatively high sensitivities, i.e., CO_2 venting during processing, CH_4 leakage in Korea, and CH_4 leakage during recovery, which would require further investigation to improve the overall accuracy of the analysis.

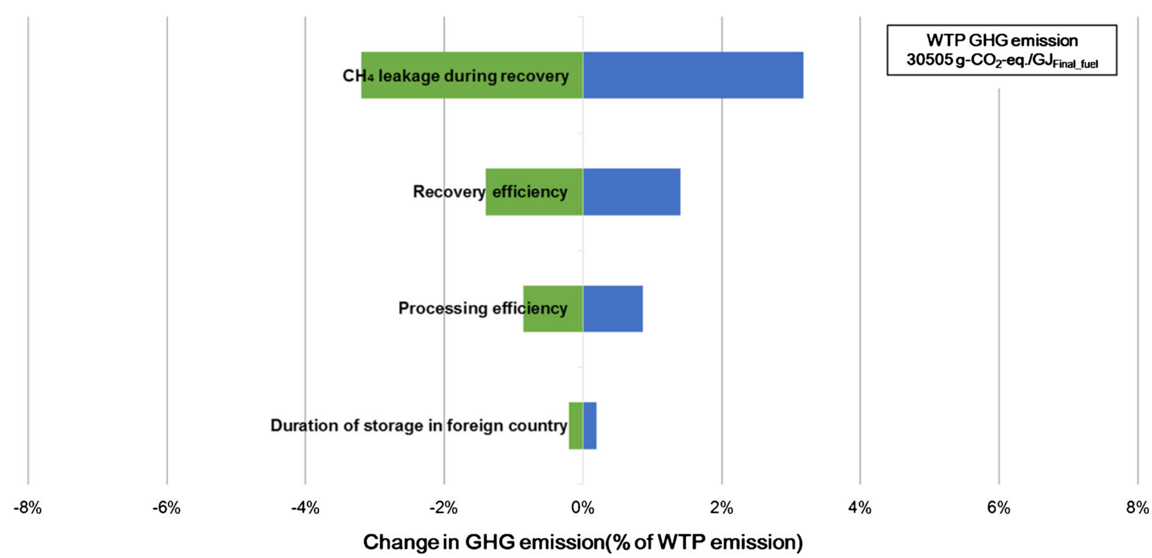


Fig. 6 Results of sensitivity analysis on WTP GHG emission by key parameters described in Table 5

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